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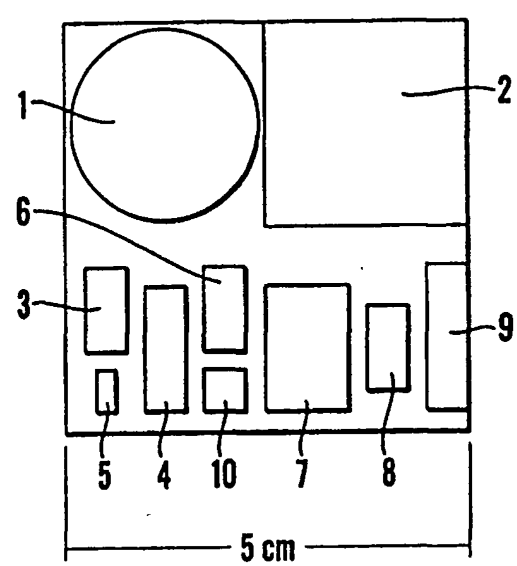
(54) Title: ENVIRONMENTAL SENSOR

(57) Abstract

An environmental sensor includes a module which comprises a plurality of sensors (4, 5, 7, 10) a memory, a battery (1) and data transfer means (6, 8). The module is able to sense data remote from a data processing station and preferably to store the sensed data for later processing. This enables the module to sense environmental conditions in circumstances where it is not possible or practicable to locate a data processing station, such as during transportation of goods and/or where there is little spare space.



Environmental Sensor

The present invention relates to an environmental sensor able to sense a plurality of environmental conditions, such as temperature, humidity, shock, vibration.

Existing environmental sensors tend to be application specific and provide sensing of only a single environmental condition. For sensing a plurality of environmental conditions, a plurality of specific environmental sensor modules are typically used. Moreover, the sensor modules tend to be bulky and expensive, limiting their use.

The present invention seeks to provide an environmental sensor module designed to sense a plurality of different environmental conditions and which is able to be used in a variety of different applications.

According to an aspect of the present invention, there is provided an environmental sensor module as specified in claim 1.

The environmental sensor can be used in a variety of applications, such as monitoring production processes, for example with in the electronics manufacturing sector. It could also be used to monitor transporting conditions, for example for any fragile or perishable goods. The sensor module could also be used to monitor service conditions of equipment or other goods.

Preferably, the environmental sensor module is self-powered, for example being battery powered. It may have sensors for sensing temperature, humidity, shock and/or vibration, or other environmental conditions.

In the preferred embodiment, the module includes a memory for recording data received from the sensors prior to transfer to a remote device. The module advantageously also includes a timing mechanism for providing a time stamp for the data read from the sensors.

The provision of an on-board memory enables the module to be used in conditions where the data would not be immediately accessible but could nevertheless be analysed at a future point in time to determine the conditions to which the module has been subjected and thereby the environmental conditions of the process being monitored. This can be particularly important in the case of perishable goods, such as foods, or during manufacturing processes where physical difficulties may arise in accessing the data read from the sensors during the processes themselves. The provision of the time stamp with the

data enables very accurate monitoring of the environmental conditions over the sensed period.

The module is preferably a small size, for example having a footprint of 2.5cm by 2.5cm and a low profile (1cm or less). Of course, other sizes of device are envisaged, although the device is preferably less than around 10cm x 10cm x 5cm.

An embodiment of the present invention is described below, by way of example only, with reference to the accompanying drawings, in which:

Figure 1 is a schematic view of an embodiment of sensor module;

Figure 2 shows in schematic form various views of an embodiment of programmable module;

Figure 3 shows in schematic form the principal components of an embodiment of reusable sensor module;

Figure 4 shows two views of an embodiment of pinned package sensor module;

Figure 5 is a schematic diagram of an embodiment of simple control logic hardware;

Figure 6 is a schematic diagram of a microprocessor-based control system;

Figure 7 is a schematic diagram of an embodiment of interrogator unit;

Figure 8 is a block diagram of an embodiment of tag unit;

Figure 9 is a schematic diagram of am example of manufacturing system; and

Figure 10 is a schematic diagram of another example of manufacturing system.

The embodiments described below relate to an example of environmental sensor module able to sense a plurality of different environmental conditions by sensors all contained within the same module and which store data within the module prior to down loading, preferably via a wireless link, to a remote device, which is preferably a data analysis station.

The preferred multi-sensor module is a small, self-contained unit which is able to fit into many different types of equipment and monitor the environment for a long period of time. The module should exhibit the following properties:

- *Small.* It should be possible to place the module in a wide range of equipment, without affecting the manufacturing process or the operation of the equipment in the field.
- *Low cost.* The cost of such a module should be low, to incur negligible effect on the

price of the equipment to which it is fitted. It could ultimately be viewed as being "disposable", with no requirement to re-use the module at a later date.

- *Robust.* It must withstand the operating conditions of the equipment into which it is placed. It must not be affected by its outside environment and it must not adversely affect the operation of the equipment into which it is placed.
- *Easy to use.* The data that is recorded must be easily recoverable without removing the equipment from its operating location.
- *Flexible.* It may be possible to change either the on-board hardware/software/firmware to allow a range of modules based around the same design. Optimised modules could be easily produced for specific applications (e.g. extreme environments, long life, etc...).

The preferred embodiment has the following specifications:

- *Temperature range*; Commercial range of around 0°C to 70°C
- *Humidity range*; At least 10% to 90%
- *Shock range*; 0g to 5g minimum
- *Cost*; £10 to £100
- *Lifetime*; 1 day (reusable) to 5 years (disposable)
- *Size*; 2.5cm x 2.5cm footprint, low profile
- *Sensor types*; temperature, humidity, shock, vibration
- *Power*; Internally powered, with possible external supply
- *Communications*; With external interface
- *Number of sensors per device*; 3 or 4

It is clear that the specifications of the device will be very much dependent on the final use of the module, but those of the preferred embodiment could be considered "baseline" values.

The scope of the module is potentially very wide, with many different options available for possible applications. The preferred embodiments are classed functionally as either "event timing" or "periodic". A hybrid design is also feasible which uses periodic sensing but also stores extreme sensor events.

Event Timing Sensor

An event timing sensor module would stay in a "sleep" mode by default, and not record any information during the standard operating environment of the equipment. Should the sensor module experience any conditions outside the allowed operating environment, the module would be "woken up" and the event time and details would be recorded.

Depending on the event, the module would either be sent back to sleep (e.g. in the case of a high g-force due to the equipment being dropped) or would remain active during the time of the environment being outside the normal operating range (e.g. outside allowed temperature extremes).

Such a module would use very little power, as it would only be in operation during extreme environments which it would be hoped would not occur often (if at all) in the equipment's time of operation . The number of potential readings the module would take would be small so the required memory store would also be small.

Periodic Sensing Sensor

An alternative provides a module which would take environmental readings, separated by a known duration. Such a module would be useful for measuring the general operating conditions of equipment to discover whether designs are failing during normal operating conditions or whether the equipment has been "over-specified" in its design.

A periodic sensor module would typically require more memory than an event sensor module and the number of memory store available to the sensor module would determine the maximum number of readings that could be taken by the module. This would determine the accuracy and sampling lifetime of the sensor module.

It is unlikely that such a module would be active all the time, it would be in "sleep" mode for the majority of time and "woken up" by a low power clock when a sample is needed to be taken.

Examples of Module Design

Various module designs are given below. To achieve a simple and cheap solution a single-sided surface mount PCB could be used in preference to more expensive double-sided

or micro-via boards. This does mean that the size of this prototype is quite large at about 5cm square. As the high cost components are the individual environmental sensors, the module would have space for three sensors but only one actually needs to be fitted for a fully operational sensor unit. Figure 1 shows an example layout for the module.

Power can be provided by a standard Lithium cell, which is used to power the microcontroller. The microcontroller provides the control electronics, as well as on-board A/D, serial I/O and timers. The only other electronics that are required are the frequency timer for the capacitive sensor and the tagging controller IC, which interfaces to the main microcontroller. Several passive discrete devices are required, however these are of negligible physical size to be of any concern to the layout. The microcontroller's on-board memory will provide the storage for the sensor values.

Table 1: Specifications for low cost sensor

Sensor Type	Event and Period
Temperature	-60°C to 300°C
Range	±10%
Shock	5g typical
Humidity	0% to 100%
Battery Life	2 years

The values given in Table 1 show the capability range of the sensors of this example. The final capabilities of the module may also depend on the packaging, substrate and interconnects used. Also, the limitation of the temperature range of the humidity sensor, for example, must be borne in mind in considering the overall temperature range of operation of the sensor unit.

The battery life is calculated on a sample being taken every minute, with the power up time being 100ms and the power up current drain being 10mA. A 200mAH capacity battery has been chosen. Negligible standby current is assumed.

By making use of a 3D build and an FPGA, another design example, much closer to a possible commercial design of the sensor module, can be built from 3 layers (see Figure 2), with patch antenna being mounted on top of the module. A double-sided or microvia PCB carries the FPGA and other ICs on the top surface, with the battery, sensors and socket being mounted on the bottom of the PCB. The specifications for the module are the same as the low-cost module, however the module is less than half the area and only 20mm longer than the final proposed size of 25mm x 25mm.

Table 2: Specifications for programmable sensor

Sensor Type	Event and Period
Temperature	-60°C to 300°C
Range	±10%
Shock	5g typical
Humidity	0% to 100%
Battery Life	2 years

The values given in Table 2 show the capability range of the sensors. The final capabilities of the module may also depend on the packaging, substrate and interconnect used.

The battery life is calculated on a sample being taken every minute, with the power up time being 100ms and the power up current drain being 10mA. A 200mAh capacity battery has been chosen. Negligible standby current is assumed.

Another example of module design, shown in Figure 3 has a footprint of 2.5cm x 2.5cm and can meet or exceed the specifications outlined above.

This module can be reprogrammed from the interrogator or electrical interface (described below). The module also has a removable battery, allowing the sensor to work over shorter periods of time and be restarted with the addition of a fresh battery. In order to allow the removable battery, the package is made from formed plastic.

This particular design allows data I/O through the tag technology described below, as well as having a small number of external electrical connections. These connections could be used in applications where the module could be easily removed and where having the high

frequency transmitter of the tag interrogator would not be attractive (e.g. in sensitive measuring equipment, or shielded equipment).

The module contains a battery as shown, and is the main constraint on length and width, and translates to a 20x20mm area. The battery provides all the power. The active parts, sensors, controller and memory are mounted on a electronics substrate, and are the limiting part of the height which will be between 20 and 30mm. The electronics substrate can be conventional epoxy reinforced resin with standard copper etched interconnects, or may however use a higher density microvia technology to improve package density.

Referring to Figure 4, another example of sensor module differs from the above examples by not necessarily being truly stand-alone. The sensor module is designed primarily for use within electrical/electronic equipment.

This sensor module is packaged as a standard 16-pin component package and is mounted on a PCB within the equipment. This packaging would provide a robust method of attaching the module to equipment, as well as providing a method of obtaining power from the equipment. A battery could be added in a modified design if required.

Communication to and from the module would be achieved through the interconnect pins. This would allow possibility of the equipment to monitor the sensor whilst in operation and the equipment's own external connectors and interfaces can provide a method for communicating directly with the module.

Processor

The amount of processing required on the module is likely to be wide ranging. For a simple module which simply records shock, temperature or humidity over time it might be possible to avoid using any processor at all by reading the output from the sensors directly into memory. Similarly in a module which is used to monitor the time instances when the environment exceeds some given limits, no processing is required; hard-wired logic can be used to read the time of the event into memory.

Processing is required for data compression which is preferably used for storing detailed sensor information. Measuring vibration is likely to require data compression, as directly storing the output from an acceleration sensor at a data rate of several hundred

samples per second (the likely resonant frequency of board units within the equipment) would require more memory than may be available to the module.

In general, the amount of processing performed by the sensor module should be kept to a minimum in order to keep the power consumption to a minimum. If more memory storage is needed than can be provided by the controller, additional memory chips could be deployed.

For an externally powered module design, care must be taken that the heat generated by the control or processing device does not affect the temperature sensor. Heat dissipation will not be a problem in the low power, battery powered device.

For a simple sensor module which requires only the storing of extreme events or simple timing information, the control functions could be performed with hard-wired logic. Here the sensor data would be read directly from the sensor and stored into the local memory. Every extreme event or timing event would cause another event time to be stored in the next available memory location. When the memory becomes full, either the module would stop further sampling or it would loop round and start overwriting earlier memory locations. Figure 5 shows a possible hardware design.

This design has the advantage of simplicity, there is no processor to program and no provision has to be made for storing the processor's program code. Not having a processor core means that the majority of the control hardware can be placed in a simple and small FPGA or ASIC.

Both Siemens Semiconductors and Motorola and planning to release combined FPGA+ memory devices, so the control, memory and timing hardware could be placed in a single device.

In order to add functionality to the non-processor design, and to increase the simplicity of the hardware design process, the "Control Logic" block of Figure 5 could be replaced by an off the shelf microcontroller. The microcontroller would not perform any processing of the sensor data, but could be programmed to perform more complex timing operations or "intelligent" data storage. The microcontroller core could be integrated into an ASIC design.

The program for the microcontroller would typically be stored in some non-volatile memory - this can sometimes be resident within the microcontroller itself. This opens up the possibility of keeping a standard hardware design and reconfiguring the module's operation by downloading a different program through the module's IO interface. The program could be

downloaded by the module's supplier after manufacture, or the module could be configured by the user. If the module was programmed by a standard PC, for example, the process could be done very easily by the end user.

An alternative to a microcontroller is the use of an Field Programmable Gate Array (FPGA). An FPGA is essentially a large array of gates which can be configured to provide the required interconnect (i.e. functionality). FPGAs come in many forms and the available functionality is determined by the number of available gates and the maximum clock speed. For a sensor module, the device could contain relatively few gates and be clocked at a low speed to conserve power.

In order to perform any amount of non-trivial processing on the sensor data, for the purpose of intelligent data storage or data compression, the sensor would need to be fitted with a microprocessor. The microprocessor would have to be very low power and, ideally, designed for applications where it would be in a "sleep" mode for long periods of time; the timer or sensor A/D could then be used to wake up the processor when a sensor reading needed to be taken.

A hybrid solution could be implemented whereby the data was read directly into the memory in a similar manner to the non-processor and microcontroller solutions and the processor would be woken up periodically to process the data. For example, if a whole day's direct sampling could be stored direct to memory then the processor could be woken up once a day to process the data and store only important events. For this application, the module's memory could be divided into a short-term memory store for the direct sensor writing and a long term data store for the processed events.

Figure 6 shows a possible microprocessor based design. It is likely that the processor will be programmed using native machine code (assembler level) due to the relative simplicity of its tasks. Using a higher level language (e.g. 'C' or Java) will reduce development times but would add unnecessary overhead to the storage required for the program memory.

<u>MEMORY</u>

The area of memory technology is developing quickly, with new technologies appearing frequently. For short term storage (up to several months), standard battery backed CMOS memory could be used but for least battery consumption and greater flexibility it is

better to use non-volatile memory. There are several technologies of non-volatile memory available (EEPROM, Flash, nvSRAM, etc...), however for the purpose of this description all these technologies have been grouped together as "non-volatile RAM". These do not require battery power to retain their memory.

CLOCK

It may be desirable to include a real-time clock in the module, if one is not present in the microcontroller or microprocessor. Real-time clocks are typically used to retain the time in equipment when power is removed, therefore they are low power devices and ideal for use in a multi-sensor module.

Some of the available clock devices contain unique serial numbers, which could be used to identify uniquely each sensor module and also create the unique key for encrypting the data, should this be required.

DATA INPUT/OUTPUT

There are two preferred approaches to getting data into and out of a sensor unit. These are by direct electrical connection or remotely via a wireless link.

This is not a demanding data I/O exercise. If it is needed, any programming of the sensor from outside and data collection from the module will require at the most a few hundred Kbytes of data in view of the low cost of the module as a whole. The rate at which data must be extracted is also not demanding and data rates as low as 20-30 kbits. second would be quite adequate to allow data transfer within 10 seconds or so. The strongest motivation is that the solution is cheap, which leads to the proposed solutions described below.

Direct Connection

A standard serial port would be quite adequate for rapid data transfer at up to 100kbits/second. This is a cheap and effective solution with the only drawback being that a physical connection must be made to the sensor. Cheap integrated serial chips are readily available.

The connection could be made either permanently through pins onto a PCB on which the sensing is being done or in the more general case for a sensor that is not located on a PCB,

it could be physically plugged into a data transfer PCB or socket to extract data and be reprogrammed as necessary.

Wireless Connection

The preferred embodiment uses tagging technology for a two-way data link. This makes the sensor module completely cordless and yet makes the data readily available to a transceiver unit placed within a few metres of the sensor. Using improved packaging technologies it is possible to produce something smaller and cheaper than has been done previously.

Referring to Figure 7, the transmitter, which is referred to as the interrogator, consists of a 2.45GHz transmitter operating at up to 100 mW which is amplitude modulated with the outgoing digital signal which may be up to 2 Mbps. This is transmitted from an antenna placed within a few metres of the tags.

The tag shown in Figure 8, is self-contained with its own battery and receives the transmitted signal through a compact patch antenna and detects it like a crystal set using a diode. The resulting digital data is amplified by an operational amplifier and cleaned up by a comparator before being fed to digital logic which contains the intelligence of the unit. The unit may or may not respond to the signal depending on whether its address matches that of the label on the data being received, much as computers on an Ethernet respond to data packets only labelled for themselves.

When the tag is asked to do or wants to send data back to the interrogator the digital logic forward biases the detecting diode which effects the RF reflection coefficient of the patch antenna. Consequently the signal being reflected back to the interrogator is amplitude modulated with the outgoing data from the tag and can be received and detected back at the interrogator unit.

This technology has several advantages over other methods such as infra red or wireless in the current application. These are:

- The tag is very simple and low cost as it consists of just a patch antenna which is an area of copper on the PCB, a diode, a single non-RF ASIC and battery.
- The battery can last years as the only significant additional current drain is in the operational amplifier which will typically draw 2μA.

• A range of over 10 metres can be achieved which is very controllable as reflected signals fall off as 4th power with distance.

• Several tags can be interrogated simultaneously through using tag Ids and a simple timing protocol.

Incorporating the tagging technology within a sensor would not add significantly to the costs as any extra cost for the patch antenna, diode and extra ASIC design would be offset by the removal of the physical connections needed to the unit.

SENSORS

There is a wide range of sensors on the market especially for measuring temperature and these output their information as a varying resistance or capacitance or digitally. The preferred sensors have the following characteristics:

- costs around £10 each or less
- less than 1 cubic cm in volume
- simple interface, such as resistance or digital.

The best source of low cost sensors was found to be the component supply companies as most low cost sensors are sold through these.

There is a large selection of temperature sensors available using a wide range of technologies including thermistors, sensing resistors and semiconductor chips. The majority give a steady change in resistance with temperature or a sudden increase in resistance at a transition temperature. Other temperature sensors give a varying current or voltage output and one gives a direct digital output which can be fed directly to digital logic. The selection for a particular application of the module should be made by considering temperature range, accuracy and cost.

Humidity

Humidity sensors are less common and generally are of the variable capacitance type. They could be monitored using a digital oscillator controlled by the capacitor. A humidity sensor would be mounted outside the enclosure or exposed at the surface to allow it exposure

to the humid conditions being monitored. In damp conditions it would be important for the sensor as a whole to be hermetically sealed to prevent moisture damage.

Shock and Vibration

Some shock and vibration sensors simply indicate when movement is detected by casing a switch. Others give a measure of acceleration through changes in its capacitance, resistance or output voltage. A common commercial use for these sensors is in the activation of car airbags.

It is important that the module should be fixed firmly to the equipment to correctly measure the shock and vibration that the equipment experiences.

Other Sensors

Other sensors of particular interest are tilt detectors which generally close or open a switch when a certain tilt level is exceeded. There are also many gas and pressure sensors that could be included, should the module require such a capability. In most cases these could be directly added or substituted within the generic module design.

Sensor Usage

Sensors with a digital output are the easiest sensor to incorporate into the module , as they can be read directly by the digital control hardware/microcontroller/microprocessor. In order to read from an analogue sensor, the analogue output must be converted into a digital form before being stored.

With a resistive sensor, the most likely method for doing this is by using an Analogue to Digital (A/D) converter. The resistive sensor would be used as half of a potential divider and the output from the potential divider would be measured by the A/D converter. A capacitative sensor would be used to drive an oscillator, and the frequency of oscillation would be measured by a microcontroller or microprocessor.

All sensors considered will allow readings to be taken on demand, however in the case of an event driven module, it will be necessary for the sensor to remain in a low power "sleep" mode until an extreme event is noticed. Resistive and capacitative sensors will require an analogue circuit or remain active at all times, and this may provide in some application an

unacceptably high drain on the battery. Using a sensor with an alarm facility which only activates under extreme conditions is therefore desirable. Table 3 shows the possible sensor types that can be used with both periodic and event driven sensor modules.

Table 3: Possible sensor types for use with periodic and event driven modules

	Periodic	**Event Driven**
Temperature	Analogue/Digital	Digital
Humidity	Analogue	----
Shock	Analogue/Digital	Digital
Vibration	Analogue	----

The reading given by most sensors will drift with other environmental factors other than the one being measured. If the module were to contain a range of sensors, it is possible to use the readings from one sensor to counteract another sensor's drift. This may be a post-processing step which would be performed after the data has been read from the sensor.

<u>BATTERY</u>

For any stand alone module, the module must receive power from an internal power source. For most practical designs, this means that the module will contain an internal battery. Each of the common battery technologies is described in the following sections. For the purpose of this description, all the items mentioned are referred to as *batteries*, even if they contain just a single cell.

<u>Rechargeable</u>

Nickel Cadmium (Ni-Cd), Nickel Metal Hydride (Ni-MH) and Lithium (Li) batteries are popular technologies which allow recharging. This makes them suitable for a reusable module which may require a large current over a short period of time. The module can then be recharged and ready to use again. Ni-Cd batteries do not come in small packages, making it difficult to incorporate them into a very small package.

Non-Rechargeable

Silver Oxide batteries provide the lowest cost form of small battery power, with a corresponding lower energy density. Silver Oxide batteries are typically single cells, and produce around 1.5v, so it is likely that two such cells will have to be used to power the sensor module.

PACKAGING

There are many packaging technologies available for containing such a module. It is likely that any low cost module will be packaged in some form of plastic or epoxy packaging, as this gives the greatest flexibility in packaging design and lowest cost in large quantities. In cases where the module is likely to be subjected to extreme environmental conditions such as high temperature or humidity, a form of ceramic or metal packaging may be used.

If a humidity sensor is to be used in the module, this must be placed external to the package.

Epoxy Potted

Using a technique such as potting, the module can be manufactured using standard PCB methods and entirely surrounded by a tough epoxy package, making the module almost indestructible.

Epoxy packaging is not fully hermetic, as moisture will be absorbed at a slow rate through the compound. This may be a problem if the sensor is expected to survive for long periods of timing a high humidity environment.

Plastic

Plastic packaging is a common form of container for a large number of volume-produced modules. Plastic is low cost and can be formed into a wide range of different configurations.

Plastic packaging is not fully hermetic, as moisture will be absorbed at a slow rate through the plastic. This may be a problem if the sensor is expected to survive for long periods of time in a high humidity environment.

Metal

The module could be placed in a metal package welded to a sealed lid. This provides a very robust hermetically sealed package and the package can be created by stamping, forging or machining from a solid block. These packages are also expensive and potentially heavy which may affect the shock and vibration measurements of the equipment being monitored. If a humidity sensor is to be used in the module, this must be placed externally.

Ceramic

Ceramic packaging is a popular method of providing a fully hermetically sealed package. Ceramic packages are typically expensive (over £10 per package), and come in simple rectangular form.

DESIGN CONSIDERATIONS

This section covers several considerations in the general design of the described modules.

Sensor Data Size

The amount of memory required for the sensor module will be very much dependent on the final capabilities of the module. What can be determined however is the amount of memory each sample reading from a sensor will require. Similarly, for an event timing sensor, the accuracy to which the time data is kept will determine the amount of memory used. It should be noted that there is no requirement to keep data sizes in any common number of bits (i.e. a byte, 16 or 32 bits) as it will be possible to use any data size with a little more design effort. The data size may also be dependent on the accuracy of the data received from the sensor (or sensor's A/D converter).

Taking an example of 8 bit data storage, the following ranges are possible:

Table 4: Sensor data storage sizes

Sensor Type	Data Range	Accuracy

Temperature	0°C to 70°C -20°C to 100°C -40°C to 140°C	Better than 0.35°C Better than 0.5°C Better than 1°C
Shock/ Vibration	0g to 5g 0g to 20g 0g to 100g	Better than 0.02g Better than 0.1g Better than 1g
Humidity	0% to 100%	Better than 0.5%

By decreasing the data storage size by a single bit (e.g. from 8 bits to 7 bits), the accuracy of the data is reduced by a half. Similarly, increasing the data storage by a single bit doubles the accuracy. For most commercial applications therefore, a data size of 8 bits is adequate and in some cases this could be reduced to increase the amount of samples possible in a given amount of memory.

For storing time data, there is again a trade off between accuracy and duration. A common method format for storing time is by choosing the number of seconds form a set time (12:00 January 1st 1980 is a common form for computers). By choosing this method, it is possible to store over 100 years of dates to individual second accuracy using 32 bits. Other possible time data sizes are given below.

Table 5: Time data storage sizes

Duration	Accuracy	Data Size
1 day	1 Second	17 bits
1 month	1 second	22 bits
1 year	1 second	25 bits
1 year	1 minute	20 bits
5 years	1 second	28 bits

5 years	1 minute	22 bits
100 years	1 second	32 bits

Sensor Data Compression

In order to increase further the amount of data stored in the sender module, it is possible to compress the stored data. It is assumed for the purposes of this description that only *lossless* compression is considered - i.e. no information is lost in the compression process.

With all the forms of compression given below, it will not be known before the data is generated how well it will compress. In a system with a fixed maximum amount of memory store (as in the case of the sensor module), this means that the number of data samples which will fill the memory is not known before the module is used.

Variable Data Size

It is possible to store frequently used data values in a shorter number of bits, with less frequently used values taking a greater number of bits; this is the basis of Huffman compression. The following table could be constructed to compress temperature data if the temperature centred around 20°C:

Table 6: Variable data size compression

Number of Bits Required	**Temperature**
3	20°C
4	19°C 21°C
5	17°C 18°C 22°C 23°C
6	etc...

This compression works well when the environment "centre point" is well known and is known to deviate little around the centre.

LZ Compression

LZ compression (named after Lempel and Ziv the creators of the algorithm) and the similar LZW (the "W" is Welch, who simplified the basic algorithm) compression algorithms work in a similar way to the variable data size algorithm. Again, common data is stored in a shorter date size, but rather than use the fixed "lookup" table of Huffman compression, the table of data and its matching variable size data counterpart is generated dynamically by the frequency of the data values to be compressed.

Typically, the data to be compressed is stored in a buffer and before compression the data is scanned for the most frequently appearing value. This value is given the shortest compressed data size. The other data sizes are allocated to the next frequently occurring data values, until all possible values have been allocated an appropriate compressed data size. The result is an algorithm which automatically adjusts for the incoming data and compresses all values well (the LZW algorithm actually builds the data size table "on the fly" rather than looking ahead at the data).

LZ/LZW compression will provide an efficient way of compressing the sensor's data for a wide variety of applications. Further details of the LZW algorithm are given in US patent no. 4,558,302.

Run-Length Compression

Run-length compression works by stringing series of the same value as a value/repeat pair. The value/repeat pair store the value, as well as the number of times this value is repeated. The table below shows how run-length compression may be used to compress temperature data as the temperature rises from 20°C to 26°C.

Table 7: Run-length data compression

Temperature	20	20	21	25	26	26	26	26	26	26

Data								
Compressed Data	20	2	21	1	25	1	26	6
Compressed Data (2)	20	2	21	25	26	6		

Run length compression works best for systems which have long runs of data of the same value (e.g. a system which experiences a small number of temperature levels). It is quite simple to improve the system to avoid any reduction in compression caused by single (i.e. non-repeating) data values.

A variation on this method of compression could simply store the value and the time, only when the value is changed.

Software Timing Algorithms

A basic period sensing module may simply take readings from the sensors at regular intervals. The interval period would be set at the time the sensor was manufactured, or programmed in the case of a reprogramable module. This potentially adds complexity to the sensor module's use, as this needs to be determined by the user before use. In the microcontroller or microprocessor based designs, it would be possible to employ smarter timing algorithms which would adjust the timing period dynamically with time.

The basis behind dynamic period timing is to choose a short time interval at the start and sample every period until all the available storage memory has been filled. At this point, the timing period is increased, and the memory is overwritten from the start except all the previous samples which are multiples of the current extended timing period are not overwritten. Once the memory has been filled again, the period is extended once more and the process repeated. The preferred algorithm allows the same sensor to be used to take many samples over a short period of tome, or fewer samples over a longer period of time.

Data Security

In order to validate the data returned by the sensor, it may be preferable to add security measures to the module to avoid the data being tampered with. It would be undesirable for the

user to be able to change the stored data to hide an extreme event in the case of a return under warranty for example. The following options may be made part of the final sensor design, as required:

- Read only sensor; the data I/O interface between the sensor and the data receiver would not allow the data to be changed in any way.
- Read and reset only sensor; the data I/O interface would only allow the date to be read or entirely erased. It would not allow individual data samples to be changed.
- Password protected; the data could be accessed by any receiver, but only with the correct password.

These methods would allow controlled access to the sensor's data through the data I/O interface. Depending on the packaging in use, however, it may be possible to access the data direct from the memory store (for example, if the memory store was a separate device). A form of encryption could the be used which would allow the data to be read direct from the memory, but it would be in a form which could not be altered without the use of the correct encryption key. Thus key could either be held by the supplier of the module, or the supplier of the equipment into which the sensor module was placed. Encryption algorithms typically add a small fixed overhead to the data size.

Similarly, an encoded checksum could be added to the data which would allow the data to be read, but any modifications would show up as an incorrect checksum; the algorithm for generating the checksum would remain proprietary.

Module Mountings

No specific description has yet been given for particular mounting methods. If the module is to measure shock or vibration, the module must be mounted rigidly to the equipment that is being monitored. This could be achieved by included screw fixtures in the case or by using an epoxy between the package and the equipment. If the package were to be presented as a leaded component DIL package the component could be soldered to the equipment PCB along with the other electronic components.

If the module is not to record shock or vibration, the module could be affixed by a simple double-sided adhesive pad. This method would require the minimum of re-design effort on behalf of the equipment manufacturer, as the module could be retrofitted to existing designs very easily.

MEASURING VIBRATION

When measuring vibration, it is important to know at least two aspects of the movement -- the amplitude and the frequency (of frequencies) of the motion. This data will require a lot of data storage within the sensor module, so a method of reducing the data down to only the important values (amplitude and dominant frequencies of the motion) is preferable. Vibration amplitude can be determined by repeatedly sampling the values from the accelerometer sensor and storing the maximum value.

Frequency can be determined by storing many sensor samples and counting the number of sample minimum/maximum data pairs; this will determine the frequency of the dominant vibration frequency. A more accurate method is to perform a Fast Fourier Transform (FFT) on the sampled data and t his will allow the calculation of all the frequency components in the sampled data. Performing an FFT requires a reasonable amount of processing time, so the FFT solution is likely to require a microprocessor within the module.

MANUFACTURE

There is a plurality of possible methods for fabricating the circuitry for the sensor module. The preferred examples are given below.

Substrate

The substrate used for the package design will usually be a trade off between cost and density. The sections below are given in order of increasing cost and density. Through hole PCB (with leaded components) has not been considered, as (i) it would not produce the required component density and (ii) many leaded components are becoming obsolete and being replaced by surface mount equivalents.

When arranging the components on the substrate, there may be a requirement to separate the sensitive sensors from the potentially high speed digital devices; this is due to

interference produced by the digital devices. This requirement may influence the sensor and digital

Microvia PCB

Although standard surface mount build PCBs are popular and could be used for this module, their interconnect density can be limited by the use of the mechanically drilled vias.

Microvia Build PCB

Microvia is just becoming a commercial process, after being available in small quantities for several years. Two technologies exist for creating the vias, either through plasma etch or laser drilling. It is currently felt that the laser drilling process is more flexible and can be used to create sub-75 μm vias - something plasma etch has not been shown to do.

Microvia PCBs (see Figure 9) are currently more expensive per layer than standard surface mount PCB builds, however the cost depends greatly on the complexity of the build. By using a greater interconnect density however, the layer count may be reduced which may lead to a reduction in cost for the board as a whole. Microvia PCBs can accommodate the same range of components (surface mount and leaded) as standard surface mount boards, but in a much smaller area (typically 30-50% smaller) and with fewer layers.

Flexi-Rigid

By using the thin polymide layers that form the outer layers of a microvia design without a rigid central core, flexible circuits can be produced. These "flexis" can be multi-layer and can be used to attach surface mount components. Combinations of flexible circuits and rigid circuits (flexi-rigids) can be constructed which can aid connection between different boards or allow interconnection between boards at different angles. Flexi-rigids typically cost about the same as microvia boards.

Silicon

The highest density of substrate interconnect is achieved by using silicon substrate (also called "MCM-D" - the "D" referring to the metal deposition process). Here, the base layer is a standard silicon wafer of the type that is used to make standard integrated circuits. Instead of

packaging the silicon in a plastic or ceramic package as would occur in an integrated circuit, the bare silicon is built on by using the same technology as microvia PCBs. Typically 2 or 3 layers of interconnect are added before adding the outer layer, onto which standard surface mount and unpackaged components can be placed (see Figure 10).

The silicon substrate not only contains very fine interconnects (typically 25 μm tracks and gaps), but can also contain active devices. If the substrate is a memory wafer for example, the substrate could be used for the storage of data with the control electronics and interfacing being present on the outer layer. This allows greater than 100% silicon to substrate ratio allowing very compact and high performance designs to be made. However the cost is several times higher than using the PCB technologies which will make it prohibitively expensive in its application. The technology has however been included for completeness and may be useful for more specialist designs.

Substrate/Device Interconnect

The most popular method for connecting devices to substrates is through solder. Soldering is a well established and low cost solution and is likely to fulfil the requirements of most electronic designs. There are other methods available for performing this interconnect which may give additional capabilities.

Spring loaded tabs or "wire wool balls" maybe used to connect either the battery or the sensors to the substrate. This would allow easy replacement of the battery in a design where the battery life was expected to be short relative to the life of the module. Similarly, solder free interconnects could be used to connect the sensors to the substrate. This would allow a generic module to be reconfigured with different sensors.

The disclosures in British patent application no. 9823158.2, from which this application claims priority, and in the abstract accompanying this application are incorporated herein by reference.

Claims

1. An environmental sensor module including a housing, a plurality of environmental sensors located within or on the housing, and data transfer means operable to transfer data from the plurality of sensors to an external device.

2. An environmental sensor according to claim 1, wherein the environmental sensor module is self-powered.

3. An environmental sensor according to claim 1 or 2, wherein the plurality of environmental sensors includes sensors for sensing one or more of temperature, humidity, shock, vibration and other environmental conditions.

4. An environmental sensor according to any preceding claim, including a memory for storing data received from the sensors prior to transfer to a remote device.

5. An environmental sensor according to claim 4, including means for compressing data prior to storage in said memory.

6. An environmental sensor according to any preceding claim, including a timing mechanism for providing a time stamp for data read from the sensors.

7. An environmental sensor according to any preceding claim, including a passive aerial array system for transferring data to a remote device.

8. An environmental sensor according to any preceding claim, including control means operable to activate the reading of data from the sensors upon detection of a predetermined abnormal condition.

9. An environmental sensor according to any one of claims 1 to 7, including control means operable to activate the reading of data from the sensors on a periodic basis.

10. An environmental sensor according to any preceding claim, including transmitting means operable to transfer said data by a wireless method.

11. An environmental sensor according to claim 10, wherein the transmitting means includes a tag.

12. An environmental sensor according to any preceding claim, including data protection means operable to prevent alteration of data read from said sensors.

13. An environmental sensor according to any preceding claim, wherein the outside dimensions of the module are around 10cm x 10cm x 5cm or less.

14. An environmental sensor according to claim 13, wherein the module has a footprint of around 2.5cm by 2.5cm.

15. An environmental sensor according to claims 13 or 14, wherein the module has a height of around 1cm or less.

16. A sensor assembly including an environmental sensor according to any preceding claim, and a device external to the module and including data receiving means for receiving data from said module and data processing means.

17. An environmental sensor module substantially as hereinbefore described with reference to and as illustrated in the accompanying drawings.

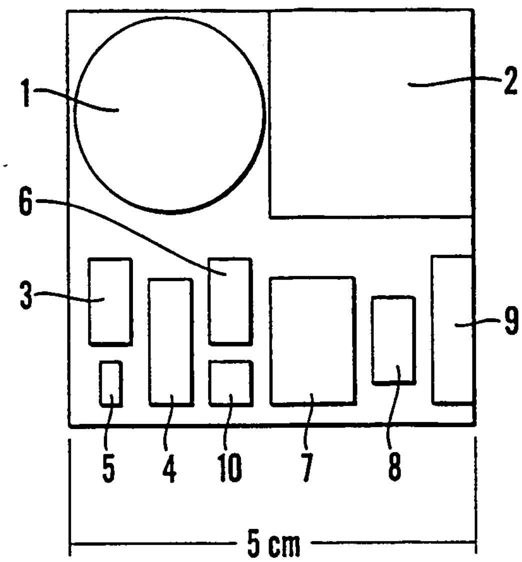


Fig. 1

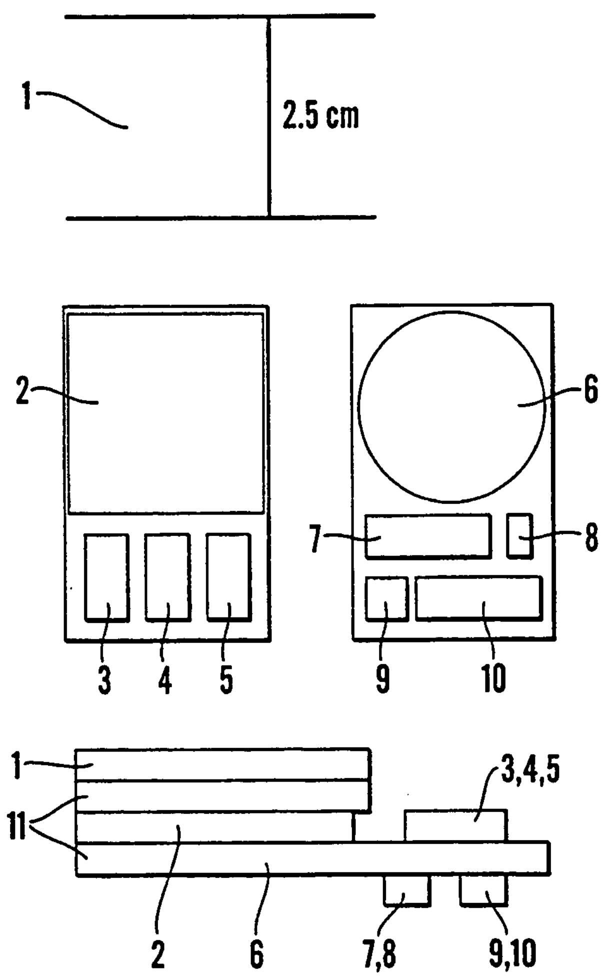


Fig. 2 LAYOUT FOR PROTOTYPE PROGRAMMABLE MODULE

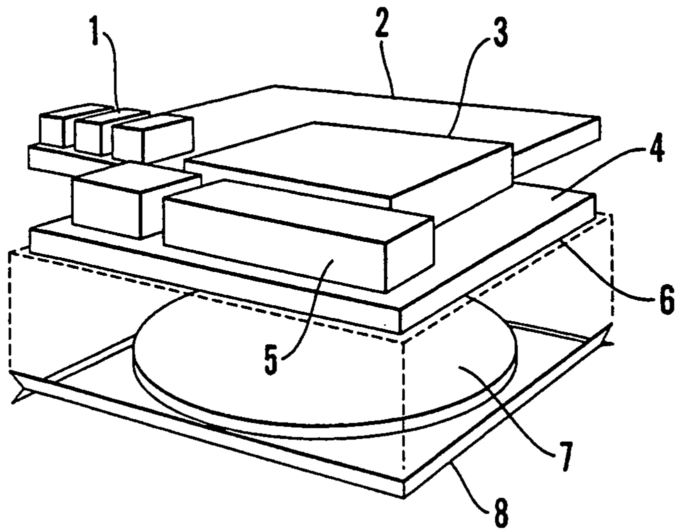


Fig.3

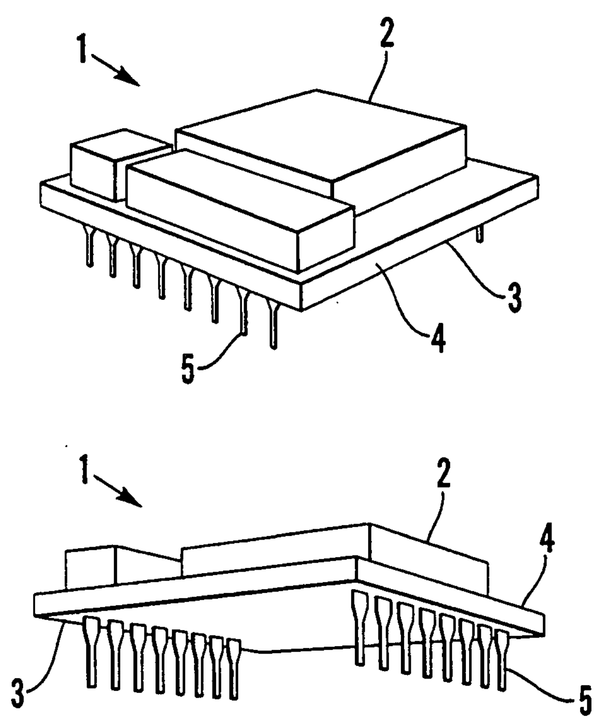


Fig.4

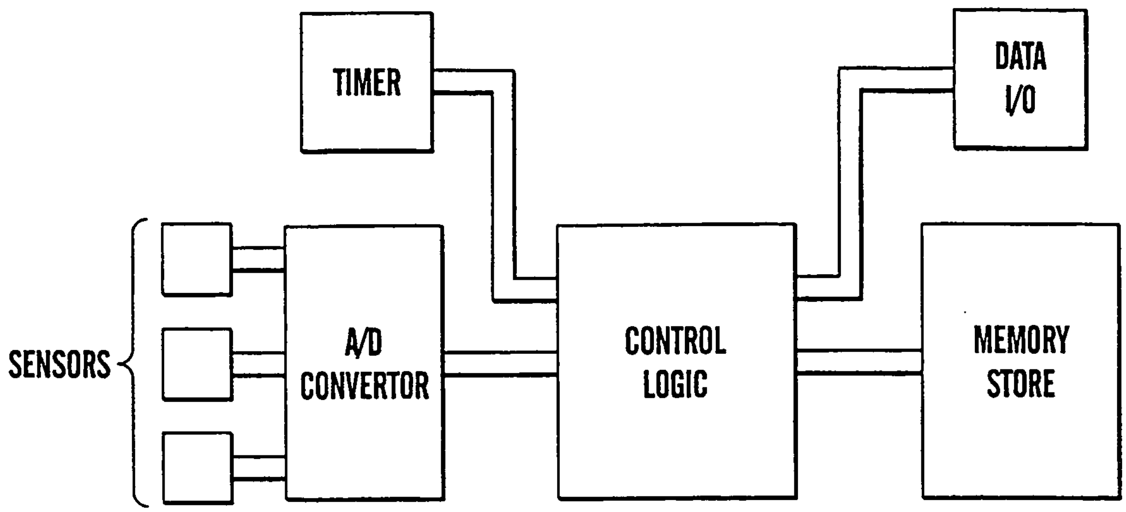


Fig.5 SIMPLE CONTROL LOGIC HARDWARE DESIGN

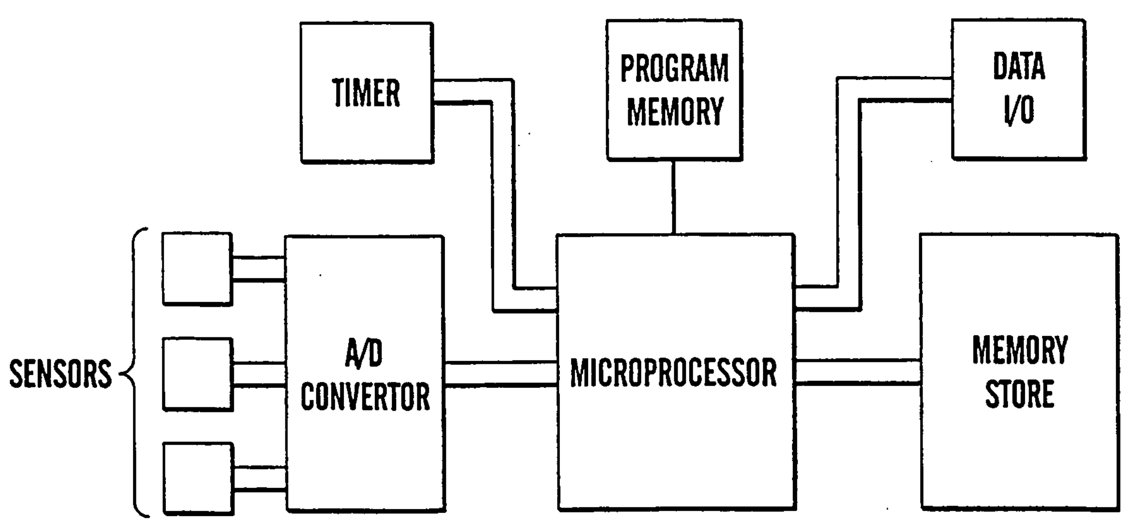


Fig.6 MICROPROCESSOR BASED HARDWARE DESIGN

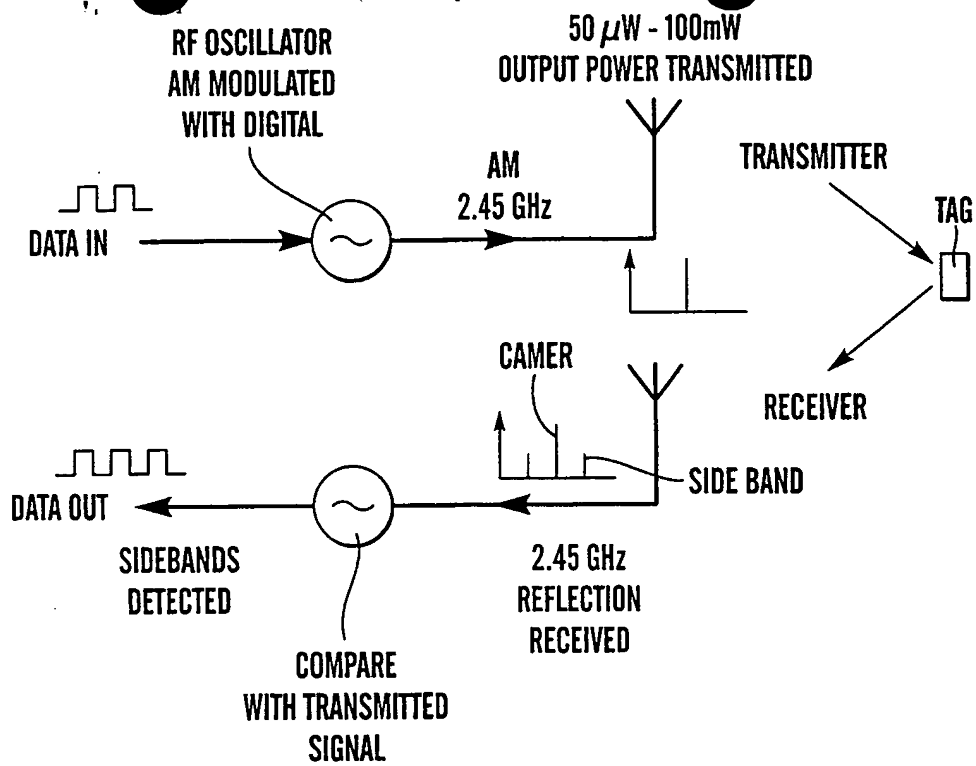


Fig. 7 BLOCK DIAGRAM INTERROGATOR UNIT

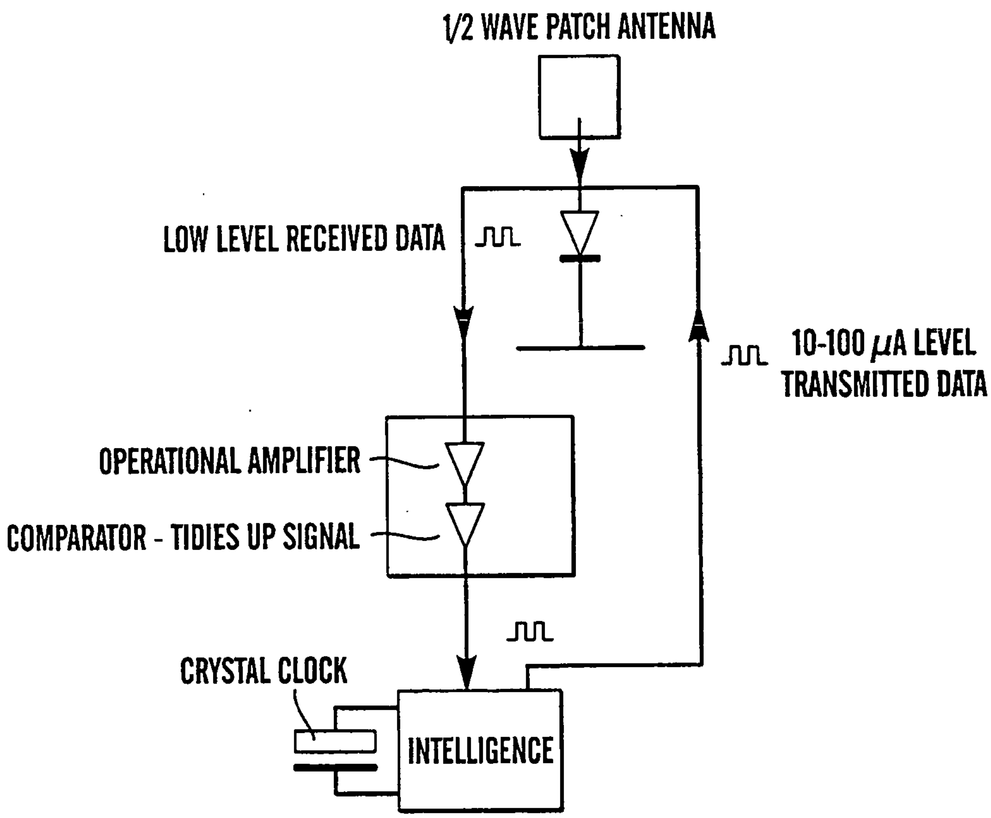


Fig. 8 BLOCK DIAGRAM OF TAG UNIT

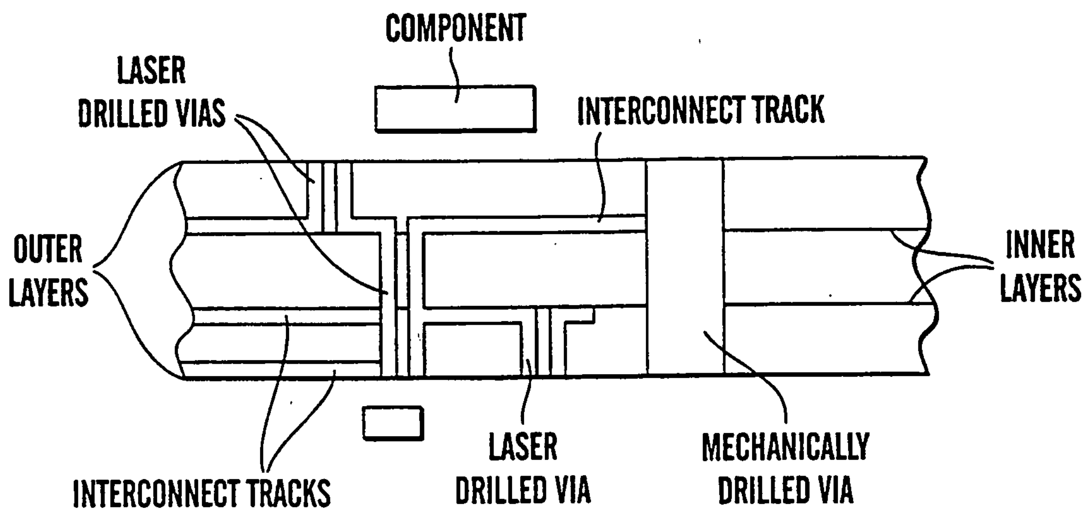


Fig.9 MICROVIA BUILD PCB

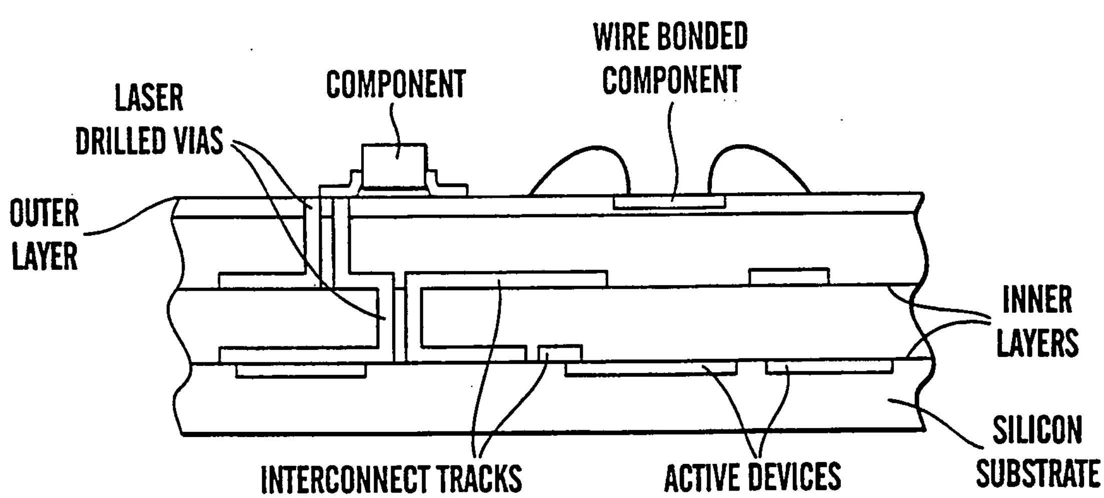


Fig.10 ACTIVE SILICON SUBSTRATE